Building Energy Benchmarking between the United States and China: Methods and Challenges

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Abstract. Currently, buildings in the U.S. account for more than 40% of total primary energy. In China the same figure is 20%. Detailed building energy analysis and benchmarking based on energy monitoring is becoming vitally important for the evaluation of energy efficiency technologies and related policy making. This paper focuses on methods and challenges in energy benchmarking of office buildings between the U.S. and China, based on the experiences and outcomes of a joint research project under the U.S.-China Clean Energy Research Center for Building Energy Efficiency. First, benchmarking methods were presented, including data analysis methods, required data, building selection criteria and a standard data model for building energy use. Annual electricity use benchmarking was performed from a sample of selected office buildings in both countries, with the aim of identifying and understanding the main discrepancies and key driving factors. Benchmarking challenges were then summarized and discussed, and some potential solutions were proposed, including the process of building selection, data collection and clean-up, and specific analysis techniques. Recommendations were proposed for future work to improve the process and outcomes of building energy benchmarking between the two countries.

Keywords: benchmarking, buildings, China, data analysis, data model, energy data, United States

1 Introduction

In 2010, China and the U.S. accounted for 20% and 19% of the global energy consumption respectively – more than any other country [1]. In the U.S., the building sector is the largest energy consumer and contributor to climate change, responsible for about 41% of U.S. primary energy use and 8% of the world's CO_2 emissions [2, 3]. China is the second largest building energy user in the world, ranking first in residential energy consumption and third in commercial energy consumption [4]. Buildings account for more than 20% of China's total primary energy consumption, and the percentage is increasing [5]. In the world, buildings are responsible for more than 40% of global energy use and one-third of global greenhouse gas emissions [6]. Most existing buildings have operation issues or deficiency, and it has been demonstrated that the problems of building energy performance are pervasive and well known [7].

In the building sector, two distinct scenarios apply: buildings in China have lower design efficiency levels but also lower needs for energy use; buildings in the U.S have higher design efficiency levels but also higher needs for energy use [8]. Generally, U.S. buildings use more energy than Chinese buildings. This is mainly driven by the differences in building design, operation and occupant behavior. Chinese buildings are usually conditioned with zonal systems such as fan coil units, and operate in a part-time, part-space mode – only occupied spaces during occupied times are conditioned. While U.S. buildings, with central built-up variable air volume (VAV) systems serving multiple zones, typically operate in a full-time, full-space mode – the whole building is conditioned most of the time, including unoccupied hours with thermostat setback [9]. Thus, while buildings in the world's two largest economies have large energy savings potential, different energy saving measures will apply.

Six factors directly influencing building energy use are climate, building envelope, building equipment, operation and maintenance, occupants' behavior and indoor environmental conditions [10]. In order to make policies that promote building energy savings, it is crucial to gain a better knowledge of these driving factors as well as the major discrepancies of energy use between buildings in the two countries. To achieve this goal, detailed building energy analysis and benchmarking based on energy monitoring system (EMS) is becoming increasingly important.

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A joint research project was conducted between Lawrence Berkeley National Laboratory (LBNL), USA and Tsinghua University, China from 2011 to 2013, under the U.S. - China Clean Energy Research Center for Building Energy Efficiency (CERC-BEE). The goal was to understand the driving forces behind the discrepancies in building energy use between the two countries; identify gaps and deficiencies of current building energy monitoring, data collection, and analysis; and create knowledge and tools to collect and analyze good building energy data to provide valuable and actionable information for key stakeholders.

However, building energy benchmarking has always been a difficult task. Though lots of efforts were made in detailed analysis and benchmarking of several buildings in this project, this paper mainly focuses on the methods and challenges during this study, to provide recommendations to improve the process and methodologies of building energy benchmarking in the future.

2 Benchmarking Methods

2.1 Data Analysis Methods

In order to understand the driving forces behind the discrepancies in building energy use between the two countries, benchmarking should be based on three levels:

1) Energy consumption of the whole building.
2) Energy consumption of major end-uses, including lighting, plug-loads, data centers and kitchens if present, elevators, domestic hot water, and HVAC systems (chillers, boilers, cooling towers, fans, pumps, DX (Direct Expansion) units and radiators), etc.
3) Performance of systems and components, including some indexes like chiller coefficients of performance, water transport factors, energy efficiency of air handling units (AHUs) and central plants, etc.

As for specific methods, energy profiling (including annual, monthly, weekly and daily energy use patterns of the whole building and major end-uses) is essential for individual building analysis and benchmarking. Energy profiling yields important information such as energy use per square meter or per capita, working days vs. non-working days (holidays, weekends), base-to-peak loads, etc.

Additionally, benchmarking should include not only the buildings in the project portfolio, but also typical buildings of the same type in both countries.

2.2 Required Data

With a clear knowledge of the goal, results, and data analysis methods to obtain the results, it is important to know what kind of data is required. First of all, detailed descriptions of building information should be collected, including not only basic information like building type, location, vintage, climate zone, floor area, conditioned floor area, operating hours, number of occupants, number of floors, etc., but also descriptions of the building envelope, HVAC systems, lighting systems, plug-load equipment as well as control and monitoring systems. Some of the basic information is of significant importance to energy analysis and benchmarking.

Measurements of the monitoring system should include three types of data:

(1) Total building energy use, broken down into major end uses for various fuel types (see 2.1);
(2) Operating conditions of HVAC systems and equipment, for example, chilled/hot water flow rates, and corresponding supply and return water temperatures;
(3) Indoor and outdoor environmental conditions, such as air temperature and humidity, outdoor wind speed and direction, solar radiation, etc.

In order to fulfill analysis with different time scales and at typical time periods, at least one complete year's valid data with a sampling frequency of at least one-hour is required.

Considering the difficulty in data acquisition in reality, data described in (1) is particularly important and necessary for basic energy benchmarking, while data in (2) and (3) is also important but optional.

2.3 Building Selection Criteria

Typical buildings from the two countries selected in this study should meet the following criteria as much as possible:

1) Medium- to large-size office buildings were preferred, as they are the most common types of commercial buildings (referred to as "public buildings" in China). The end uses of such buildings can be more easily clarified as there are not so many special devices or complicated systems as in

other building types, such as hospitals and shopping malls.
2) Required data discussed in 2.2 is available.
3) Overview of the monitoring system showing the hierarchy of sub-metering is available.
4) High-level description of BMS (Building Management System) – what data points are available.

2.4 Energy Data Model

After detailed and valid data is collected, it is necessary to analyze energy usage based on different end-uses. Contributions were made during this project to develop a uniform data model, certified in the ISO Standard 12655, Energy Performance of Buildings - Presentation of measured energy use of buildings [11], shown in Fig. 1.

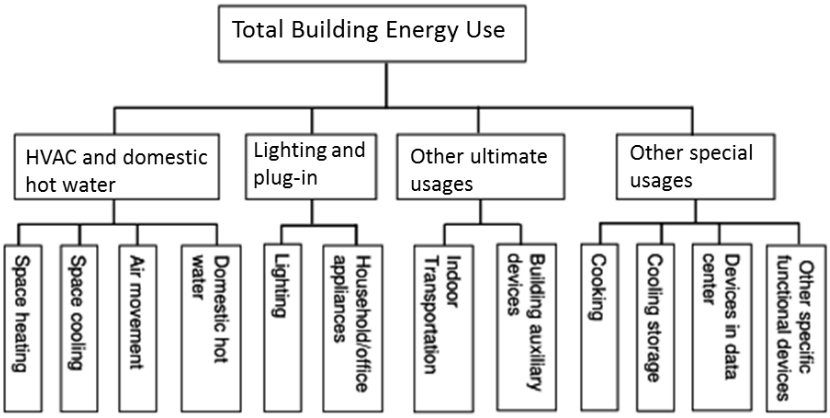

Fig. 1 Data model of energy use in buildings

This model follows a tree structure, from total energy use down to each major end-use. End-uses in both the first and second tiers are described clearly in this standard. Ideally, it can be applied in most buildings, and benchmarking can be performed across buildings based on these detailed end-uses.

3 Benchmarking Case Study

3.1 Introduction of Selected Buildings

A dozen office buildings in the U.S. and China were selected for this project. Four of them, for which the data collection and initial analysis has been completed, were used for benchmarking. Table 1 summarizes some basic information of these buildings.

Table 1 Basic information of the case study buildings

Name	Building A	Building B	Building C	Building D
Location	Beijing, China	Beijing, China	Merced, California, U.S.	Berkeley, California, U.S.
IECC Climate Zone	Zone 4B	Zone 4B	Zone 3B	Zone 3C
Year of construction	1989	1987	2005	1960
Floor area (m²)	54,490	39,211	16,000 (7,000 for the office wing)	8,316
Operation hours	M-F 7 a.m.-6 p.m.	M-F 6 a.m.-6 p.m.	M-F 7 a.m.-6 p.m.	M-F 7 a.m.- 6 p.m.
HVAC	Water-cooled chiller, district heating, VAV + CAV systems	Decentralized AC for cooling, district heating	District cooling, district heating, VAV systems	Local electric cooling and gas-boiler heating packaged DX systems
Monitoring platform	iSagy	iSagy	EPP (Energy Performance Platform)	Pulse Energy
Data time-interval	1 hour	1 hour	15 min	15 min

Building A is a large, mixed-use commercial office building with some restaurants, stores, and a bank. It consists of a tall main building with large glass curtain walls and an annex. Building B is a government administrative office building, served by decentralized cooling systems and district heating with radiators, without any other air-side equipment. Building C is a mixed-use building with a library wing (9000 m²) and an office wing (7000 m²), and is served by district cooling and heating systems. Only the office wing is considered in this study. Building D is the oldest among these four buildings, with metal-panel walls without insulation; and leaky, single-pane, clear-glass windows. It is served by various DX HVAC systems.

3.2 Benchmarking of Case Study Buildings

Energy benchmarking was conducted among the selected buildings based on annual, monthly, weekly and daily time scales. However, in this paper only the annual analysis is presented as an example.

As shown in Fig. 2, the annual total electricity consumption intensity of each building is broken down into four major subcategories, which slightly distinguish from the first tier end-uses in Fig. 1, due to the inadequate sub-metering in some buildings. Typical office buildings in both countries were also included in this benchmarking. The typical Chinese office building is the average of 513 office buildings in Beijing, China [12], while the typical U.S. office building is the average of 112 office buildings in California, U.S.[1].

Because of the lack of gas metering for space heating in the Chinese buildings served by the city-wide district heating systems, only electricity was considered and space heating source energy was not included in the HVAC category. However, energy used by equipment related to space heating (pumps, AHUs, etc.) is still included. The subcategory "Other" in Fig. 1 describes energy-using devices such as elevators, data centers, kitchen equipment, hot water boilers, water supplying and draining pumps. However, in Building D, some special equipment which should have been categorized as "Other" was actually included in "Office Equipment", due to the lack of sub-metering.

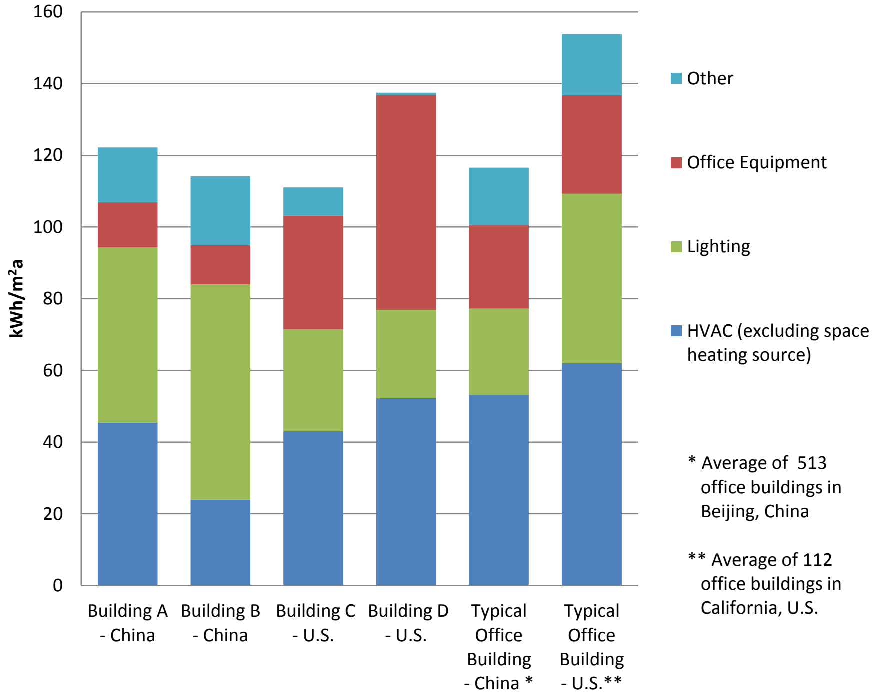

Fig. 2 Comparison of annual electricity consumption of the case-study buildings and typical office buildings in China and the U.S.

For total annual electricity use, Buildings A and B performed similarly to the typical Chinese office building. However, the two U.S. buildings, particularly Building C, consumed much less than the typical U.S. office building, mainly due to more efficient lighting and HVAC systems.

In terms of HVAC performance, Building B consumed the least electricity, indicating that decentralized HVAC systems may perform more efficiently than centralized HVAC systems. Building D, though located in a mild climate, consumed more HVAC energy than the Chinese buildings, which may be

[1] California Commercial End-Use Survey, http://energyiq.lbl.gov/

caused by several factors. First, Building D's indoor temperature setpoint for cooling is 21 to 22℃, lower than Building A's 24 to 26℃. Second, Building D's old, leaky and uninsulated envelope results in much higher cooling and heating loads. Finally, in general, more ventilation air is provided in the U.S. buildings. U.S. ventilation standards are more stringent than in China, leading to more electricity used to condition outdoor air.

As for lighting, the Chinese buildings consume much more energy than the U.S. buildings. This may be a combination of design and operation: lighting power, occupant density, operation mode of lights, and utilization of natural light. According to real-time data, Building B's lighting system consumes more electricity not only during daytime, but also at night, contributing to the greatest lighting energy use among the buildings. On the other hand, Building D's single-pane windows introduce more natural light, and its lighting system has undergone some retrofits. Occupancy sensors in Buildings C and D turn off lights when occupants leave the office. However, the typical office building in the U.S. consumes more lighting energy than the typical building in China, demonstrating that in general, lights in most U.S. office buildings are on for most of the time and without occupancy sensor control.

The two U.S. buildings, particularly Building D, consume much more electricity by office equipment than the two Chinese buildings. Many computers in Building D are left on or in standby mode at night for remote logon, data backup, system operating or security software updates. This building also has more personal fans, heaters, and desktop task lights, leading to higher energy use.

Generally, more energy saving potential was identified from lighting measures for the two Chinese buildings, and from office equipment measures for the two U.S. buildings. There are various reasons for these discrepancies. More buildings with detailed information are needed to figure out common discrepancies and their key driving factors, and retrofit measures.

4 Challenges and Discussion

4.1 Building Selection

4.1.1 Lack of Data

A large number of commercial buildings in the U.S. have some kind of EMS installed. The newer buildings with Leadership in Energy and Environmental Design (LEED) certification require building monitoring as a part of the commissioning process. However, many buildings that claim to have EMS lack detailed component-level measurements, so hourly or sub-hourly data was unavailable in most buildings.

It is common to see a lack of data for environmental and HVAC operating conditions in buildings with EMS, especially in China. Some buildings installed with energy management and control systems that can monitor and control indoor conditions as well as energy end uses in real time, are unfortunately not connected to a monitoring system to store the data for a long period of time. More seriously, there is a lack of heating energy data for Chinese buildings served by city district heating systems. All of these problems set limitation to building selection in this project, and the selected buildings may not meet all criteria.

4.1.2 Data Sharing and Communication

The willingness of building owners to share data, and communication with building managers are also barriers to energy benchmarking. First, many owners are worried about privacy and security concerning real-time data. Second, such an energy saving project may not be on the high priority list of building owners and managers. Therefore, energy data and detailed information about the whole building, systems and even particular equipment may not be available. These problems have to be overcome by personal communication, site visits, nondisclosure agreements, the promise to share analysis results and identify retrofit measures, and sometimes even by government mandatory policies. It is important to convince building owners and managers of the benefits of such an energy saving project and inform them of their responsibilities and the kind of information they may provide throughout the project.

4.2 Data Collection and Clean-up

4.2.1 Data Retrieval

Even when access to building information databases is permitted by the operators/managers, it is still a labor-intensive procedure to download or export the data. Some systems require software written in specific computer languages to retrieve and export data, which may add complications. Moreover, downloaded datasets may change unnoticed when the same operations are conducted repeatedly.

More importantly, although raw data may be sampled over short intervals by EMS, such as five-minute intervals or even less, the frequency of the data available for download can be different, depending on what time intervals are used for post-processing of the raw data. In this project, 15-minute interval data were downloaded for the two U.S. buildings, and hourly data for the two Chinese buildings.

The difficulty and reliability of data retrieval and the availability of data at certain intervals depends on the EMS. The features of some existing systems were reviewed in some studies [13, 14]. Improvements to data retrieval, downloading and exporting features would ease data acquisition and contribute to data with smaller time steps and fewer manual errors.

4.2.2 Naming of Data Points

Poor naming conventions of data points in some EMSs have led to confusion, incompleteness and other mistakes in data collection. Consistent and clear naming conventions for data points are becoming more crucial as computerized systems containing hundreds of data points are deployed in commercial buildings. Well-chosen data point names can provide useful information about installed systems and make it easier to monitor, retrieve and download, analyze, maintain, modify, and interconnect data from various building systems [15].

4.2.3 Data Quality

Most selected buildings have some missing data, and there seems to be no pattern to describe which meters might lose data and when. Meter instability may cause occasional individual missing data, while large sets of missing data may be caused by the retrofit of either the monitoring system itself or energy service system (like HVAC or lighting). Data loss may also be caused by power failure in the buildings, during which the meters don't measure, the connection is lost, and even the computer is out of power. To avoid these problems requires higher quality meters, sensors, nonstop operation of the monitoring system, and better emergency measures or backup systems when power is out and connection is lost.

Even if the data obtained are complete, data quality may suffer, mainly due to un-calibrated or broken meters and sensors. Some invalid data — such as negative values and abnormal spikes — can easily be detected, while some seemingly normal data may actually be inaccurate, considering the error of measurement. Higher quality meters and sensors, along with more frequent maintenance, would avoid these problems.

It is possible for missing or invalid data to appear during the downloading and exporting process, especially when exporting a large set of data at one time. A higher quality data transmission system may avoid this possibility.

4.2.4 Data Clean-up

To get the data in workable order for analysis, missing or invalid data should be replaced with data during time periods or days that were similar to the invalid points, taking weather conditions into account. For example, a few missing data could be replaced by the previous or following proper data, or their average. Several hours' missing data could be replaced by data of the same time period from the previous or following day, taking into account weekdays and weekends respectively. The same applies to missing or invalid data from even longer period.

4.3 Specific Analysis Challenges

4.3.1 Mixed-use Building

In reality, most buildings are mixed-use buildings to some extent, and thus separating spaces with different usages (office, retail, library, etc.) is a big challenge. For buildings with large spaces for one type of usage and only small spaces for other usages, such as Building A and B which have small restaurant areas, it can be unnecessary and sometimes impossible to separate. While for buildings with comparative spaces of different types, a nearly half-library and half-office building, there should be a way to separate the spaces. Take Building C for example, the energy use of the office wing can be calculated by multiplying the energy use of the whole building by the area ratio of the office wing, in this case 7/16.

4.3.2 District Cooling/Heating System

District systems are common for heating in Chinese buildings, or buildings that are part of a campus network for American buildings. Thus, related energy use data particularly for individual buildings are unavailable, in terms of equipment such as chillers, boilers, pumps, and cooling towers.

However, there is a way to estimate such energy use. First, calculate the ratio of the cooling/heating load consumed by the individual building to that supplied by the plant. Then, multiply this ratio by the energy consumed by the plant to get a rough estimate of the building's energy consumption associated with heating/cooling. Such an estimation method was applied to Building C during this study. However, it is still impossible to estimate heating source energy for Chinese buildings served by district heating systems.

4.3.3 End-uses Comparison

Though the ISO standard data model was proposed, each building has its own particular sub-metering system that is not compliant with the ISO standard. It is hard to take full advantage of the data model to categorize and compare energy use at various end-use levels thoroughly.

Separating mixed end-uses is always a big challenge. In some cases, there are certain methods within the monitoring system to separate mixed end-uses, such as lighting and plug-loads. For example, the Optimization of Adjustment Algorithm [16] is adopted for the EMS in Building A and B. In some other cases, total consumption of mixed end-uses and the consumption of one specific end-use are metered, and thus the energy consumption of the other end-uses can be calculated. However, when neither of the above methods is applied to a building, comparison can be difficult. In most buildings, public service and special equipment are usually not metered separately. Take Building D for example, equipment in the kitchens and data center are mixed with office equipment, leading to the difficulty in comparison based on major subcategories.

Besides, the lack of gas metering of space heating in Chinese buildings makes the HVAC energy benchmarking insufficient, due to the exclusion of not only the space heating source energy, but also the terminal reheat in VAV systems commonly used in the U.S. buildings.

4.3.4 Normalization of Energy Use

Energy use normalized by floor area, number of occupants, operating hours or cooling/heating degree days (CDD/HDD) is important for benchmarking. However, the related data may not be accurate despite being available. For example, floor area is a key factor for calculating energy use intensity and benchmarking, but the real definition of it varies a lot in different references about some buildings. Whether garage, restaurants, podiums or any other special spaces are included, and whether walls are considered, can be confusing, especially for buildings with spaces for different usages. Moreover, air-conditioning floor area is even more complicated and less reliable. Therefore, the inaccuracy of floor area may lead to incorrect conclusions from benchmarking.

The number of occupants and operating hours provided by building managers may be inaccurate or out of date, since it changes with time. The reliability of CDD/HDD data also needs consideration, as it was calculated with some approximation methods. Consequently, deeper benchmarking cannot be conducted precisely with normalized energy use.

4.3.5 Typical Buildings

Acquiring energy use data for typical buildings of the same type as case buildings throughout a country is a big challenge for benchmarking. Though there are some national or state surveys on energy consumption for lots of buildings of each main type, only annual data based on a few major subcategories are available, limiting the depth of benchmarking between case buildings and typical buildings. The accuracy of average energy use based on such databases depends highly on the number, variation and typicality of surveyed buildings, and how thoroughly the survey was conducted. A good example is given by the deviation of the lighting energy comparison between case buildings from that between typical buildings in both countries.

5 Conclusions

Building energy benchmarking is becoming crucially important for energy savings in the U.S. and China. Based on the actual experience and outcomes of energy benchmarking between several office buildings in the two countries, benchmarking methods and challenges were discussed in this paper. Some basic recommendations for future benchmarking work are summarized as follows:

1) Install well-designed EMSs at the beginning of building construction and improve the features of the whole system, to get complete and valid required data, so that benchmarking based on the standard

data model can be conducted. Specifically, the U.S. buildings should focus more on detailed sub-metering for different end-uses and data quality, while Chinese buildings should install more sensors and meters for environmental conditions and HVAC monitoring, add district heating information and related data, and increase the time resolution of data available for download.

2) Include more buildings and other building types in energy benchmarking to identify and understand common discrepancies and their driving factors, and feasible retrofit measures. More emphasis should be put on communication with building owners and facility managers, to gain better knowledge about the building characteristics and operation.
3) Increase the accuracy and reliability of some key data related to building energy benchmarking, such as floor area, operating hours and so on.

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